Constellation of cubesats: 3-star in the humsat/geoid mission

CONSTELLATION OF CUBESATS: 3-STAR IN THE HUMSAT/GEOID MISSION

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The 3-STAR program is the new cubesat educational project at the Politecnico di Torino. It has been thought in response to the GEOID call for proposals issued by the Education Office of the European Space Agency. The GEOID (GENSO Experimental Orbital Initial Demonstration) initiative wants to settle an orbiting constellation of cubesats to be operated by the GENSO (Global Educational Network for Satellite Operations) ground-stations network. GEOID is expected to be the communication backbone of the initial version of the HUMSAT system. The main goal of HUMSAT is to use the constellation of satellites and the GENSO ground stations, to provide support for humanitarian initiatives, especially in developing areas or areas without infrastructure. The 3-STAR will be one of the nine cubesats in the GEOID constellation. It will be a 3U cubesat derived from the e-st@r cubesat experience. In addition, it will carry two payloads: the HumSat payload, consisting of a simple but extremely reliable communication module compatible with the elements of the HUMSAT system, and the P-GRESSION (Payload for GNSS remote sensing and signal detection) payload. The P-GRESSION payload aims at performing measurements by means of radio-occultation technique and scattering theory, using GNSS signals. In this paper the 3-STAR project is described together with a preliminary assessment on the performances of the GEOID/HUMSAT constellation. The main requirements of the GEOID/HUMSAT project have been used to drive an optimization process aimed at determining the best configurations of a swarm-like constellation of cubesats. The mission scenario is made of the nine GEOID cubesats, a number of GENSO ground nodes and several sensors distributed on the Earth surface. The results of the analysis demonstrate that the aspects related to the cubesat-system design cannot be decoupled from the design of the constellation, not even in a preliminary phase. Further, it is demonstrated that the performances of a swarm-like constellation are comparable to those of a *well-distributed* one.

NOMENCLATURE

3STAR	3U SaTellite At politecnico di toRino
ASSET	AeroSpace System Engineering Team
GENSO	Global Educational Network for Satellite Operations
GEOID	GENSO Experimental Orbital Initial Demonstration
HUMSAT	Humanitarian Satellite Network Project
OCF	Orbit Cost Function
P-GRESSION	Payload for GNSS Remote Sensing and Signal detectION

I. INTRODUCTION AND BACKGROUND

3STAR is an educational project which is being developed by a multidisciplinary team of students from several engineering departments of Politecnico di Torino. The project is coordinated by the AeroSpace Systems Engineering Team (ASSET) at the Aerospace Engineering Department and involves researchers and students from several engineering areas: Aerospace , Electronics, Energetic, Automotive, and Management. In particular, the Electronics Department (DELEN) represented by the Remote Sensing Group (RSG) and the Navigation Signal Analysis and Simulation Group (NavSAS) is responsible for the P-GRESSION (Payload for GNSS Remote Sensing and Signal detectION) payload. The 3STAR mission consists of a 3U Cubesat orbiting the Earth and acting as a data-relay platform and a space-based test bed for an Earth remote sensing experiment. A dedicated ground control station is also included in the mission. The final goal is to test a network of ground stations, and to provide communication capabilities in cases of natural disaster, for specific areas of the globe, and for scientific purposes. The 3-STAR mission has been thought within an ESA program proposed by Education Office, named GEOID acronym of GENSO Experimental Orbital Initial Demonstration. GEOID is an initiative for the promotion of Space activities in European University, by settling an orbiting constellation of Cubesat to be operated by the GENSO network. GEOID initiative is strongly linked to HUMSAT program which has been proposed to the European Commission by a

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team of Universities, supported by ESA and United Nations.

At the Politecnico di Torino, several teams are involved in designing space missions and systems. Among these, the AeroSpace Systems Engineering Team (ASSET) of the Department of Aeronautics and Space Engineering, has been carrying out programs on small space platforms for many years. In the last decade, the team has focused the attention on the development of small satellites for educational and research purposes.

The first program was the PiCPoT nano-satellite, which ended in 2006. The PiCPoT satellite was developed and launched, but unfortunately it never reached its intended orbit due to a failure in the launch vehicle occurred a few seconds after liftoff. Notwithstanding the unsuccessful launch, the project represents an important stepping stone in terms of knowledge and educational relevance.

The heritage of PiCPoT has been reaped by the e-st@r program, which is now approaching the finish line [1]. The e-st@r program, mainly educational, has been selected by the ESA Education Office as one of the nine university Cubesats on the Vega maiden flight. The e-st@r project has been carried out by a team of about 30 students, graduate and undergraduate, and some PhD students also participated in the program. Some of those students are also amongst the members of the proposing team for the 3-STAR project. Professors and researchers of the ASSET team acted as supervisors, dealing also with management issues. The launch of the Cubesat is now scheduled to take place in first quarter of 2012.

II. THE 3STAR MISSION

The mission objectives for the 3STAR project have been derived from the mission statement:

> *"The project aims at educating and inspiring space engineering students on complex-systems development and operations, international cooperation and team work. The mission wants to contribute to the humanitarian exploitation of Space, by supporting communications capability in developing countries and/or allowing areas without infrastructure to access space-based services, and to enhance the knowledge on remote sensing applications for future small space missions."*

The following objectives are derived from the mission statement:

- The program shall have educational relevance: hands-on practice education and training of students on a real spacecraft project
- The mission shall carry one or more payload related to the peaceful and humanitarian exploitation of space.
- The mission shall demonstrate one or more remote sensing applications based on non-space-qualified systems.

The 3STAR program is developed at university level, so the main objectives are both the scientific and the educational relevance of the activity. The main constraint is represented by the limited available budget for the program development. Figure 1 illustrates the guidelines which are assumed as high level objectives and constraints for the program. In

Figure 2, we present the logical process implemented to obtain the scientific objectives of the mission. Taking into account those assumptions the mission and system requirements can be established, and the technical specifications can be derived for both the space and the ground segments.

The primary objective for 3-STAR program is to support and contribute to the HUMSAT and GEOID missions. In particular, several primary program sub-objectives can be defined:

- To provide telecommunications services in support to humanitarian and emergency applications
- To monitor parameters related to climate change
- To settle international collaboration among universities and research centres from all over the world
- To validate the GENSO network on a large-scale basis
- To promote high-level education on space systems

However, the 3-STAR project has a challenging additional objective: to perform on orbit remote sensing measurements, employing different remote sensing techniques for Earth observation, atmosphere profiling for climate studies, and eventually warning services [3] [4] [5] [6]. The P-GRESSION multi-purpose payload is under study at the moment and the first application will be implemented soon on a test bench.

Secondary objectives are the set up of permanent space education project based on small-missions development and the test of low cost technologies in orbit to facilitate future small space missions.

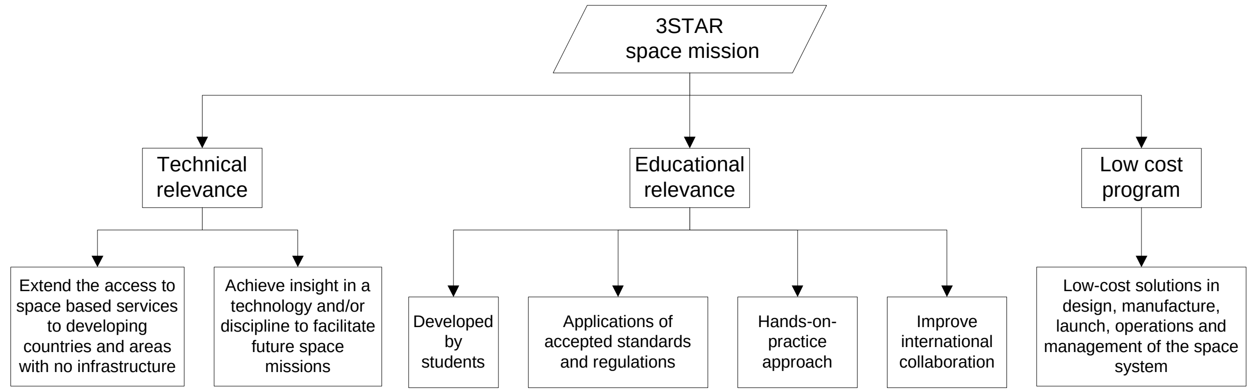


Figure 1: 3STAR project drivers

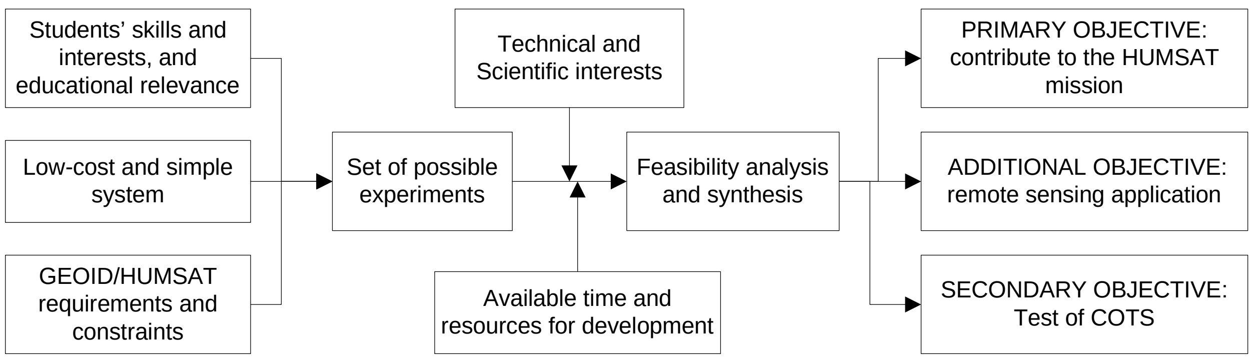


Figure 2: Technical objectives definition

<u>Mission architecture</u>

The diagram in Figure 3 presents the 3-STAR mission architecture and its elements:

- The Space segment is composed by a 3U Cubesat encompassing 3-STAR bus and two payloads
- The Ground segment is composed by a main ground station, a mobile and transportable backup station, and the GENSO stations network. Radio-amateurs can receive Cubesat signal but they can't command it.
- The Subjects are the Earth surface and the Earth atmosphere, and sensors distributed over the Earth surface.
- Launch vehicle, launch site and the final orbital elements are not defined yet.
- Communications are maintained and managed, according to the HUMSAT requirements and IARU regulations.
- Operations will be managed by operators at GENSO stations and by the student at the main and back up station.

The Cubesat can operate in different ways, depending on the mission phases, considering that the 3-STAR cubesat hosts two payloads. Some operative modes have been identified and described in Table 1.

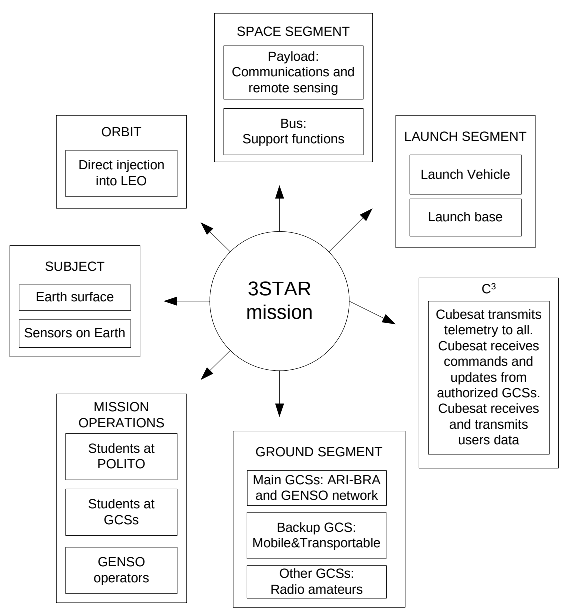


Figure 3: 3-STAR mission architecture

Table 1: 3-STAR Operative modes

Operative mode	Description
LEOP	Cubesat immediately after launch and during commissioning is tested to prepare next mission phase
HUMSAT Mission	Cubesat is used as an element of Humsat constellation
P-GRESSION Mission	Cubesat is used as a remote sensing space platform
Basic Mission	Cubesat is used as space test bed for COTS equipment
Safe Mission	Off-normal mode, set in case the cubesat presents some failures and needs to be restored
Dormant	During launch the Cubesat's systems are deactivated. The Cubesat may be turned on the dormant mode also upon request of international authorities or HumSat mission control board

III. GEOID/HUMSAT CONSTELLATION

The main drivers for the GEOID/HUMSAT project have been used to set up an optimization process aimed at determining the best configurations of a swarm-like constellation of cubesats, [2]. The study foresees the deployment of a constellation formed by nano-satellites and ground stations to provide communication services between different locations on Earth with a store-and-forward architecture. Initially there will be 9 cubesats. The number of cubesats is then increased to 12 to study the effect on the performances and constraints, in perspective of an eventual expansion of the constellation. Some considerations on the effect of losing some satellites are discussed as well.

For the design and the optimization process of the constellation we defined 2 main objectives: a figure-of-merit of the cost of the constellation and a figure-of-merit of the global coverage.

The qualitative measure of the cost of the constellation is based on the number of satellites, the number of different orbital planes, the Orbit Cost Function (OCF, ΔV for each satellite) scaled on the interval [max OCF / min OCF], and the eccentricity of the orbit. The objective is to minimize the cost.

$$N°Orbits = 1 + \frac{N°Orbital\_planes}{Max\_N°Satellites} \tag{1}$$

$$ToGetThere = 1 + \frac{\left(\sum_{N°Sat} OCF_{sat} \cdot (1+e) - MinOCF\right)}{MaxOCF - MinOCF} \tag{2}$$

$$\begin{aligned} MinOCF &= 7.797 \\ MaxOCF &= N°Satellites \cdot 13 \cdot (1+0.9) \end{aligned} \tag{3}$$

$$Cost = ToGetThere \cdot N°Orbits \tag{4}$$

The global coverage of the Earth surface is studied on a time basis using the GAP-time between two useful passages over all the ground stations. The GAP-time is scaled over the interval between zero and the maximum GAP-time. The objective is to minimize the global gap.

$$1 + \frac{\left(\sum_{N°Sat.} \sum_{N°GroSt.} GAP\_Time - MinGap\right)}{MaxGap - MinGap} \tag{5}$$

$$\begin{aligned} MinGap &= 0 \\ MaxGap &= SimulationTime \cdot N°GroundStations \end{aligned} \tag{6}$$

In Table 2, the positions on the Earth surface of the ground stations considered for the analysis are summarized. Some of these ground stations are also official GENSO nodes. Some other stations, instead, have been added to test the constellation performance for additional GENSO nodes or areas on the globe to be reached by the GEOID network. All the ground stations are considered accessible by the satellites with a relative elevation angle of at least 5°.

Table 2: Ground stations and GEOID sensors.

Ground Station	Lat. [°]	Lon. [°]
GS1, Torino	45.03	7.4
GS2, Vigo	42.9	-8.4
GS3, CalTec	34.09	-118.07
GS4, Japan	35.26	139.5
GS5, ISU Strasbourg	48.34	7.4
GS6, Surrey	51.3	-0.2
GS7	17.25	95.21
GS8	19.09	-72.09
GS9	-68.4	-60.21
GS10	-16	-37
GS11	0	-77
GS12	76	-41
GS13	34	64
GS14	-75	-123
GS15	68	114

Two constraints are taken into account in the analysis. The perigee altitude must be larger than 200 Km (thus with limitations on the eccentricity for a given semi-major axis, see Figure 4) and the link margin must be larger than 3dB.

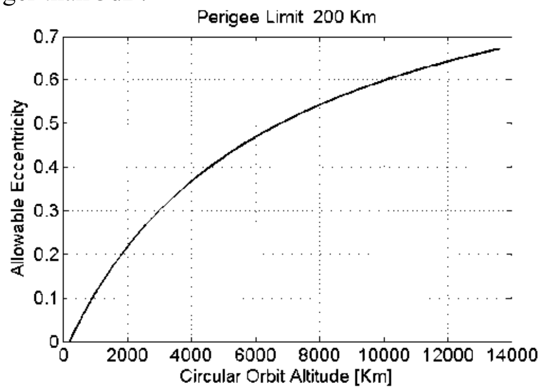
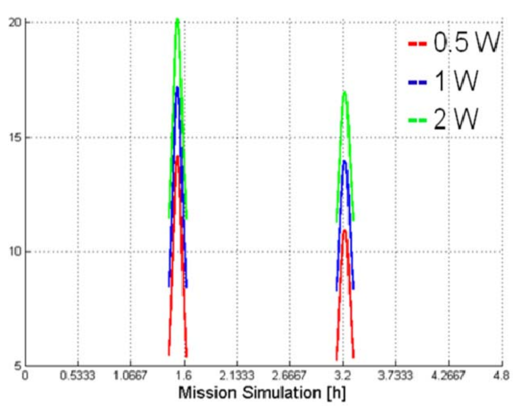
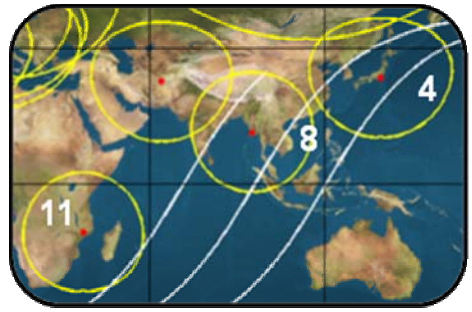


Figure 4: Eccentricity constraint as a function of the orbit circular altitude for a perigee altitude limit of 200 km.

For the determination of the link-margin constraint, only the downlink between the satellites and the ground stations has been considered. The communication frequency has been set to 437.445 MHz, with a bitrate of 9600 bps, and a bit-error-rate of 10^{-5}. In Figure 5(a), the link margin for a hypothetical passage of a cubesat over the ground station 4, i.e., Japan, is computed as a function of the transmitter output power of the communication subsystem. As expected, a large output power yields to a large link-margin that is also function of the distance between the satellite and the ground station. This is demonstrated by the parabolic behavior of the link-margin, with a maximum at the point of minimum distance between the cubesat and the ground station. In Figure 5(b) the ground track of the satellite and the access area of the ground stations are visualized.



(a)



(b)

Figure 5: (a) Link margin expressed in dB for the passage over the GS4 (Japan). (b) Ground track (white) and access area (yellow) over the ground stations (red spots).

With the purpose of understanding the performances of some known constellation configurations, some preliminary analyses have been performed, before initiating the optimization process.

In Figure 6, a constellation of 9 cubesats with 3 orbital planes with inclination equal to 97° is presented. The cubesats are well distributed along the orbits that are all circular.

On the X axis of the graph we report the GAP figure-of-merit. On the Y axis the cost figure-of-merit is considered, instead. As expected, with an increasing value of the semi-major axis, the GAP decreases (so the coverage increases) while the cost of the constellation increases. Further, the higher the altitude gets, the lower the gain in coverage for further increase of the altitude is, until the link margin constraint is violated (10000 km for instance).

In Figure 7 a swarm-like configuration is presented. There is a uniform distribution of the orbital planes, and a non-uniform distribution of the cubesats within each plane. This is what would happen if the constellation would be built with 3 launches, each with 3 cubesats, for instance. The red-star symbols of the graph in Figure 7 are computed with the same semi-major axis settings of Constellation 1 (whose design points are represented by the black diamond symbols in Figure 7). It can be observed that the GAP figure-of-merit is similar to that computed for Constellation 1 in case of low orbits while it is larger in case of higher orbits. The cost figure-of-merit is always the same to that computed for the Constellation 1.

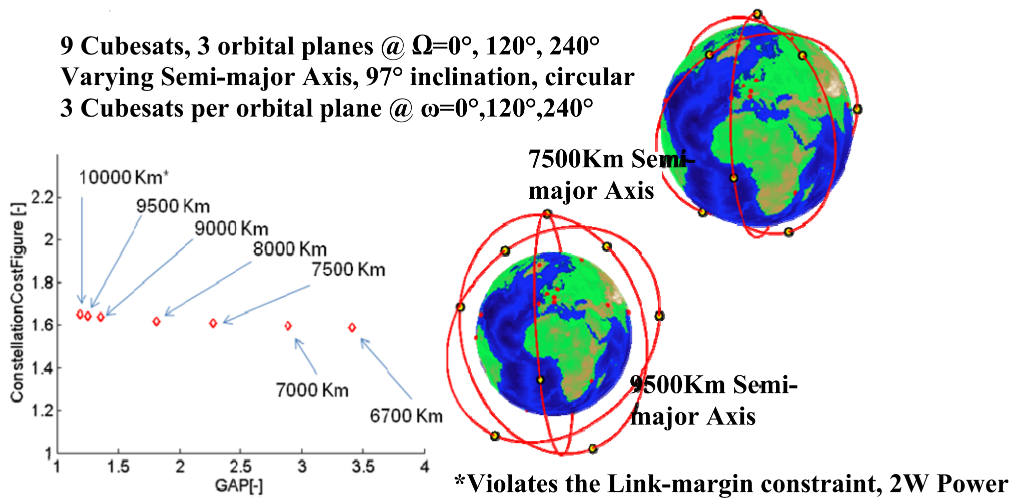


Figure 6: Constellation 1

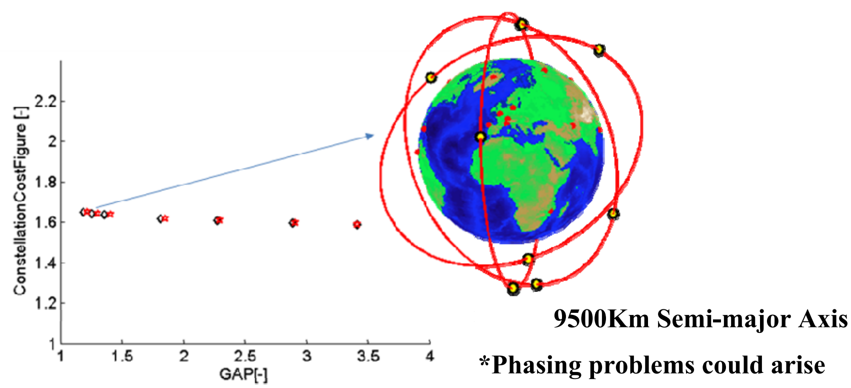


Figure 7: Constellation 2

The 9-cubesats configuration for the GEOID mission is the nominal final one. There can be cases, however, of cubesats loss, and certainly phases of the mission in which the constellation is being built-up. Therefore, we studied the performances of the constellation in case of 8 and 7 cubesats, in several configurations. As we expected, with a reduced number of cubesats the cost figure-of-merit decreases while the GAP figure-of-merit increases, see Figure 8. In a more optimistic vision, we decided to study the constellation with 12 cubesats instead of 9. The purpose is to study the performances of an expanded version of the GEOID baseline. As expected we obtain increased performances in terms of coverage but also an increased cost figure-of-merit, see Figure 9.

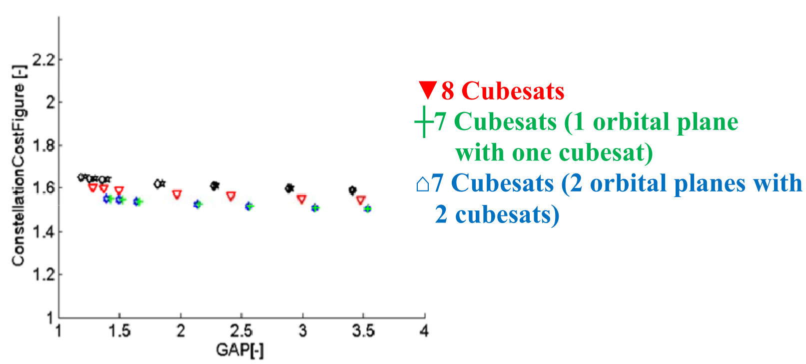


Figure 8: Constellation sensitivity to cubesats loss.

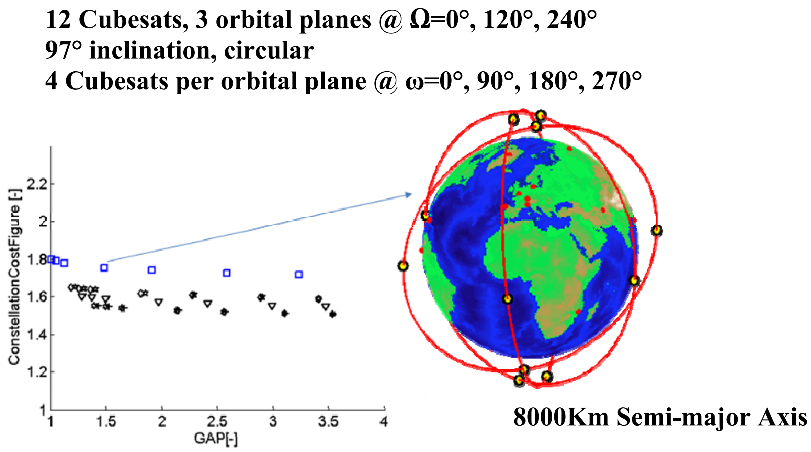


Figure 9: Constellation with 12 cubesats

So far, the results obtained from the study of the constellation with the objectives and constraints mentioned before are quite logic and corroborate what one could in principle anticipate. This is a promising conclusion if seen in perspective of an optimization process to be executed on the mathematical model of the constellation of cubesats.

Further, the configurations previously described are also useful to better understand the results coming from the optimization process.

We used a NSGAII algorithm with 9 cubesats, thus 54 design variables (6 orbital elements per cubesat), the 2 objectives of cost and GAP and the 2 constraints of orbit perigee altitude and link margin.

The results of the optimization process are presented in Figure 10.

The yellow circles represent the numerical Pareto front obtained using the perigee altitude constraint only. The solutions mostly present 3 orbital planes, swarm-like constellations, circular orbits, and with an inclination that is very close to the launch latitude (supposed Baikonur). To improve the GAP performance the altitude must increase until configurations are obtained for which full coverage during the simulation time is achieved (the yellow circles overlapping the Y axis of Figure 10, i.e. with the GAP figure-of-merit equal to 1).

The optimization process has been executed considering also the link-margin constraint, with the transmitter output power at 2W, 1 W and 0.5 W. As can be observed in Figure 10, in all the cases the solutions arrive at a certain point on the objective space from which an improvement in the GAP figure-of-merit can only be obtained at a much larger cost figure-of-merit. Until that point, the coverage is improved by raising the altitude of the orbits until the link-margin constraint allows it. From that critical point, the improvement is achieved by increasing the inclination of the orbits or/and the number of orbital planes.

In Figure 10 two extreme examples of constellations are visualized: a low-cost and low-coverage constellation with inclination of 50° and semi-major axis of 6600 km, and a high-cost and high-coverage constellation with 7 orbital planes at 8000 km of semi-major axis and 90° of inclination (streets-of-coverage constellation).

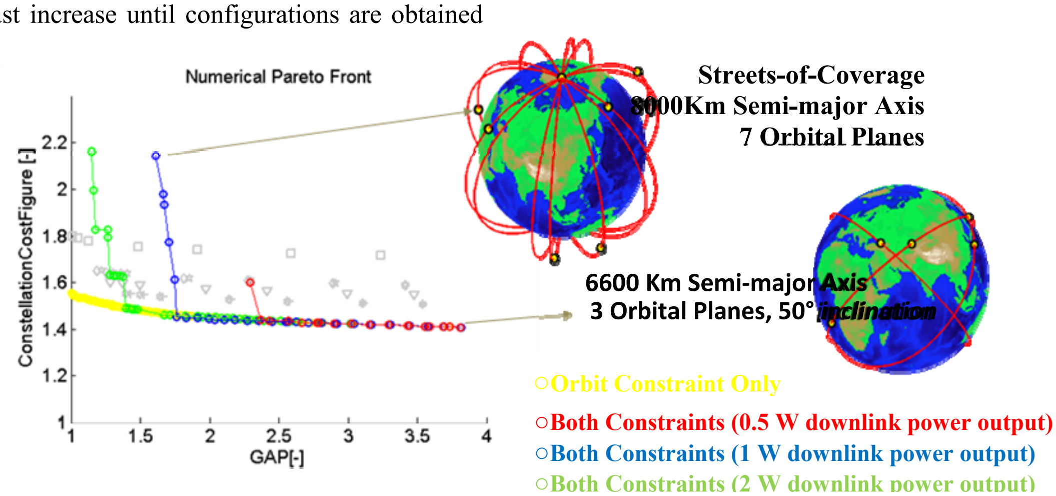


Figure 10: Results of the optimization process using a 9-satellites constellation of cubesats.

IV. CONCLUSIONS AND RECOMMENDATIONS

The mission of 3-STAR has been thought within an ESA program proposed by Education Office and named GEOID, acronym of GENSO Experimental Orbital Initial Demonstration, that is an initiative for the promotion of Space activities in European University, by settling an orbiting constellation of Cubesat to be operated by GENSO Stations Network. The 3-STAR program is devoted to support the HumSat program, which has been proposed to the European Commission by a team of Universities, supported by ESA and United Nations.

First of all, educational aspects of the program are taken into account. In fact, using hands-on practice approach allows students to learn how to handle real engineering problems and solve them in the most effective way. In addition, the international spirit of the project gives the opportunity to meet other university space mission developers and to cope with external entities, in order to improve social and professional skills.

3-STAR is intended to support Humsat/Geoid purposes by implementing a store-and-forward communications system.

A very challenging aspect of the project is to implement remote sensing applications and test on orbit a simple and cheap system for remote sensing completely developed within the Politecnico di Torino.

The results obtained studying the performances of a constellation of cubesats show very promising perspectives, even though they are certainly not exhaustive nor covering all the aspects related to cubesats constellations. The results presented in this paper shall be considered as preliminary results also driven by the way the objectives are determined. We would like to stress the fact that swarm-like constellations show performances that are comparable to well-distributed ones. Further, systems constraints cannot be neglected even during mission design. As demonstrated before, the link-margin constraint posed non-negligible restrictions on the design of the constellation and it will affect the entire cubesat system-architecture design.

V. ACKNOWLEDGMENTS

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REFERENCES

[1] S. Chiesa, S.Corpino, F.Stesina, N.Viola, *"CUBESATS DEVELOPMENT AT POLITECNICO DI TORINO: THE E-ST@R PROGRAM"*,. 61th International Astronautical Congress 2010.

[2] S.Corpino, G.Ridolfi, F.Stesina, "*Constellation of Cubesats: a preliminary assessment on the performance of the HUMSAT/GEOID mission"*, presented at 1st IAA Conference on University Satellite Mission and Cubesat Workshop

[3] Martin-Neira, M. Caparrini, J. Font-Rossello, S. Lannelongue, C. S. Vallmitjana, *"The PARIS concept: an experimental demonstration of sea surface altimetry using GPS reflected signals*", IEEE Transactions on Geoscience and Remote Sensing, 39, p. 142, 2001

[4] D. Masters, S. Katzberg, P. Axelrad, "Initial results of land-reflected GPS bistatic radar measurements in SMEX02", Remote Sensing of Environment, Volume 92, Issue 4, 30 September 2004, Pages 507-520

[5] Scott Gleason, Mounir Adjrad and Martin Unwin, *"Sensing Ocean, Ice and Land Reflected Signals from Space: Results from the UK-DMC GPS Reflectometry Experiment",* Journal of Space Communications, 2005.

[6] M. Cucca R. Notarpietro, M. Fantino; G.Perona, "*REFLECTED GNSS SIGNALS RECEIVED ON UNMANNED AERIAL VEHICLE PLATFORM: A FEASIBILITY STUDY*", In: Proceedings of the 2010 Gold Remote Sensing Conference, 2010 Gold Remote Sensing Conference, Livorno, Italy April 29-30, 2010, 2010